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Highly effective system for excitation and reception of Lamb waves in ferromagnets

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Abstract. The paper presents the concept of a highly efficient system for excitation and reception of Lamb waves in ferromagnets. Methods for creating large polarizing fields allowing to increase the efficiency of generation and reception of Lamb waves in ferromagnets and the principles of unidirectional electromagnetic-acoustic transducers are proposed. The results obtained in this work can be used in the development of devices for non-destructive testing of the long ferromagnetic objects.

1. Introduction

Nowadays, the non-contact ultrasonic electromagnetic-acoustic (EMA) non-destructive testing of ferromagnetic products and structures is promising [1, 2]. Of particular interest is waveguide method implemented by using Lamb waves. The method helps to scan the entire surface of the test object, since wave propagates through the object as a waveguide. Thus, in just one pass along the object, information about the defects contained in it can be obtained. The main disadvantage of the EMA method compared to contact ultrasound is the need to use strong magnetizing fields. The magnitude of these fields directly affects the conversion efficiency of electromagnetic and acoustic oscillations and therefore sensitivity to defects. For this reason EMA transducers (EMATs) are large and they are strongly attracted to the surface of a ferromagnet. In addition, there is the problem of ambiguity in determining the coordinates of defects due to the fact that the EMA transducer emits waves in all directions. This paper is devoted to the development of the emitter-receiver system with an increased efficiency of EMA conversion and lacking the listed disadvantages.

2. EMAT excitation and reception system

Highly effective system for excitation and reception of Lamb waves in ferromagnets must include EMATs that emit and receive waves in one direction only and also have magnetizing system with an optimal polarizing field. In ferromagnets there mostly work two EMA conversion mechanisms: electrodynamic and magnetostrictive. To amplify any of these mechanisms, either a tangential or a normal polarizing field must be applied to the ferromagnetic object. The maximum efficiency of magnetostrictive EMA conversion is achieved at a magnetic field strength of about 300 A/cm [3]. The efficiency of electrodynamic EMA conversion increases with an increase of the applied field. When the material is inducted above 1.2 T the efficiency is comparable with the maximum possible efficiency of a magnetostrictive EMA conversion. It is possible to create such polarizing fields only through the use of special magnetizing systems [4].

2.1. Unidirectional primary EMATs

The principle of unidirectional primary EMATs is used in EMATs of the highly effective system [5].

Primary EMAT consists of two nested in each other meanders coils with a phase shift of a quarter of the length of the ultrasonic wave (figure 1).

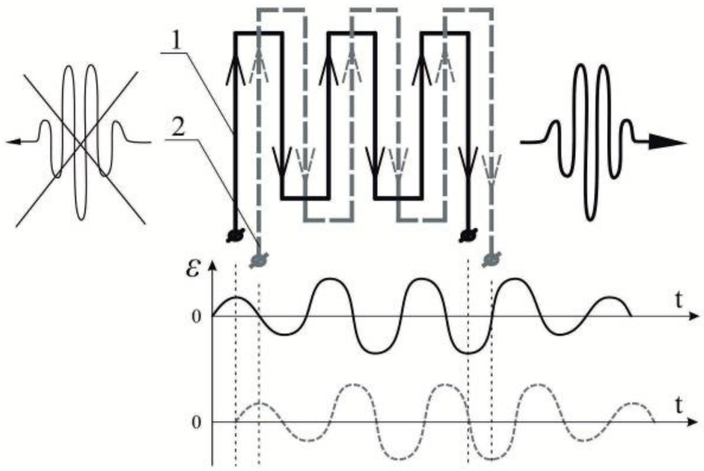

Figure 1. Scheme of the inclusion of primary unidirectional EMA converters: 1 - external coil, 2 - enclosed coil.

The signal from the probe pulse generator is also shifted in phase by 90 degrees in such a way that amplification of the amplitude of the ultrasonic wave propagating to one side of the primary EMA transducer (excitation coil). And there occurs almost complete attenuation of the wave, propagating to the other side. The signal from the receiving nested coil is digitized separately and then also shifted in phase. This gives signal filtering and additional amplification. Thus, to obtain a single measurement, it is necessary to generate an ultrasonic wave two times - on each side of the emitter.

2.2. Permanent magnets magnetizing system

It is advisable to create a normal magnetizing field by using a magnetizing system with a non-collinear arrangement of permanent magnets. The direction of polarization of each individual magnet is based on the considerations of maximizing its contribution to the field created in a given area of space. The fields from different magnets can be combined (including counter direction) with each other without changing the characteristics of each magnet. Figure 2 shows a simulation results in the FEMM program of magnetizing system built according to the principle of noncollinear arrangement of permanent magnets. The direction of magnetization of each individual magnet was chosen based on the fact that the field along the magnetic field line is greater than the field along any other direction. Thus, if at the point where it is planned to create the maximum field, place a point dipole with polarization along the field being created, then the lines of force of this dipole will show the optimal polarization direction of the magnets, which create the required field.

The results showed that with a 10 mm gap between the magnetizing system and the object surface the magnetizing system creates a magnetic induction of about 2.25 T in the ferromagnetic material. But it is very difficult to make such a system: it requires hundreds of magnets with different directions of magnetization and a complex mandrel for assembly. Therefore, by successive simplification the system shown in figure 3 was obtained. Induction in the working area of this system is less than ideal, but still close to optimal.

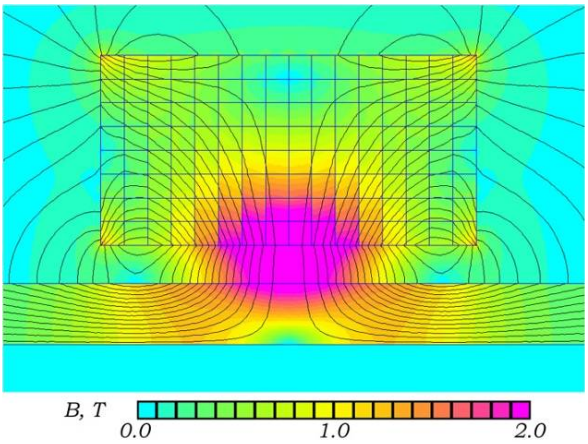

Figure 2. Distribution of magnetic induction for the *optimized* magnetizing systems with noncollinear arrangement of permanent magnets.

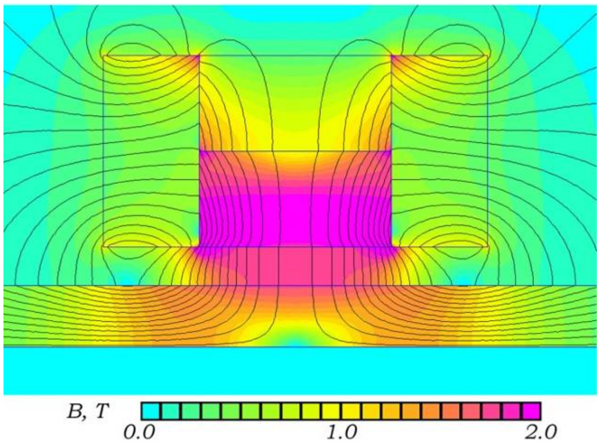

Figure 3. Distribution of magnetic induction for the *simplified* optimized magnetizing systems with noncollinear arrangement of permanent magnets.

A simplified magnetizing system was made of rectangular magnets. The magnetic system is a core of magnetically soft material (FeCo) of a cubic shape 40 × 40 × 40 mm, surrounded on all sides, except for the working, with permanent high-energy magnets, so that the polarization directions of the magnets are directed inside the core. The dimensions of the system are 90 × 90 × 40 mm and the weight without a mandrel does not exceed 2.8 kg. The magnetic induction in the working area reaches 1.3 T and this agrees well with the simulation results.

2.3. Pulsed magnetizing system

Because of the difficulties in working with permanent magnets the idea to use a U-shaped pulsed electromagnet that does not contain permanent magnets as a magnetizing system has occured. The essence of a pulsed magnetizing system is that during a short pulse, a probe excitation pulse is applied. In this case only the surface layer of the ferromagnet is magnetized due to the short duration of the bias pulse (~ 100 μs). It is considered that with tangential magnetization by a U-shaped electromagnet, the ferromagnet thickness plays an important role: the larger it is, the more difficult it is to create the required magnetic field due to the magnetic flux spreading deep into the ferromagnet. Pulse magnetisation in ferromagnetics generates eddy currents that "push" the magnetic flux onto its surface. Therefore, there is no need to magnetize the ferromagnet throughout its thickness. It is a significant advantage of using pulsed magnetization**.** In addition, you can use a short pulsed bias that will significantly reduce the energy consumption of the pulsed electromagnet due to the shorter duration of the magnetizing pulse, the smaller depth of the skin layer, and so it is easier to create the required magnetic field in it.

To determine geometric and electrical characteristics first of all it is necessary to take into account the nonlinearity of the magnetic properties of ferromagnets when calculating the depth of the skin layer. Thus, the skin layer of a U-shaped magnet material must be in the linear region of the magnetization curve (figure 4) and a typical equation (1) can be used to calculate the skin layer:

$$\Delta = \sqrt{\frac{2}{\omega \cdot \sigma \cdot \mu}} \tag{1}$$

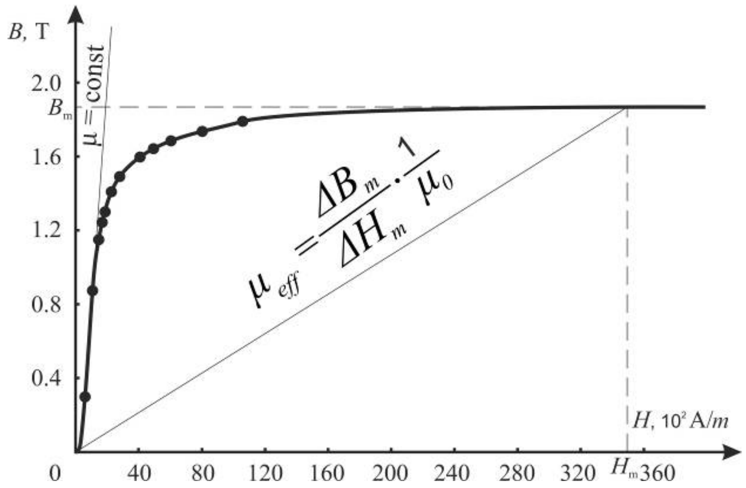

Figure 4. Steel 20 magnetization curve.

At the same, time the skin layer of the ferromagnetic object is in deep saturation (H = 350 A/cm), i.e. the magnetic permeability μ can be represented as μ_{eff} and substitute it into the following equation (2) for calculating the skin layer for the nonlinear case.

$$\Delta = \sqrt{\frac{2}{\omega \cdot \sigma \cdot \mu_{eff}}} = \sqrt{\frac{2}{\omega \cdot \sigma} \cdot \frac{H_m}{B_m}} \qquad (2)$$

The geometric and electrical parameters of a pulsed magnetizing U-shaped system must be calculated and optimized taking into account the specified field value, the dimensions of the EMA transducer coils for exciting Lamb waves, as well as the gap between the electromagnet pole and the surface of the ferromagnet. For these purposes you can use the equations obtained in [6] when calculating the magnetic circuit using analogs of Ohm and Kirchhoff's laws.

The magnetizing system with the calculated parameters was made. The figure 5 shows the obtained oscillogram of the probe pulse against the background of the biasing pulse.

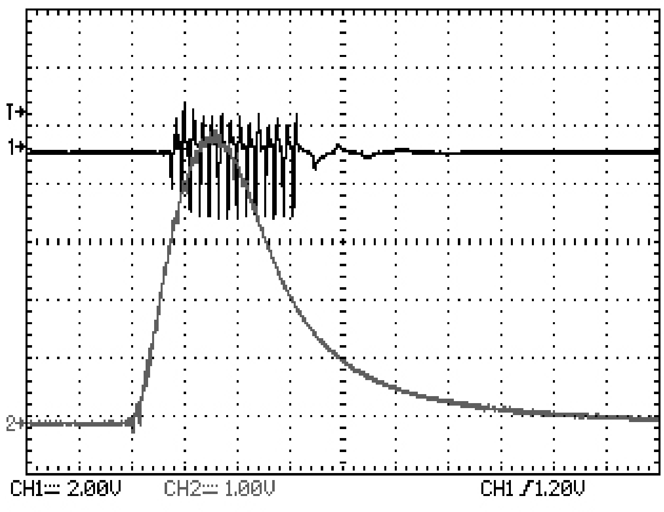

Figure 5. Oscillogram of the probe pulse against the background of the biasing pulse.

Experiments made with pulsed U-shaped magnetizing system have shown that the magnitude of the signal obtained with its help is comparable to the magnitude of the signal obtained using an optimized system with non-collinear arrangement of permanent magnets (figure 3). When the current in the pulse coil increases from 50 to 100 A, the efficiency of EMA conversion at first increases, and at a current above 80 A starts to decrease slowly. This indicates that at a current of 80 A, the field in the working area of the pulsed electromagnet is about $350 \cdot 10^2$ A/m.

2.4. Excitation magnetostrictive transducer

The next step is a complete rejection of the magnetizing system due to the EMA excitation of ultrasonic oscillations at double frequency. This method does not require a bias field and is based on the parity of the magnetostriction effect (figure 6): the change in the size of a ferromagnet in a magnetic field does not depend on the direction of this magnetic field.

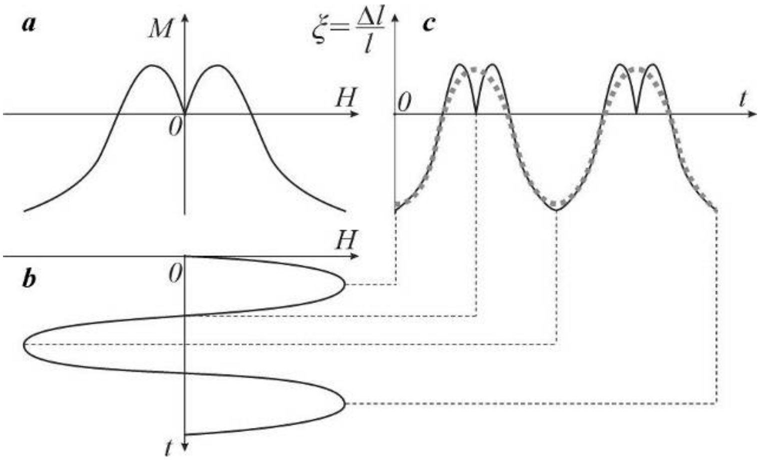

Figure 6. Illustration of the parity of the magnetostrictive effect: a - dependence of the magnetostriction coefficient $M = f(H)$ on the magnetic field H; b - change in the magnetic field strength $H = f(t)$; c - sample deformation.

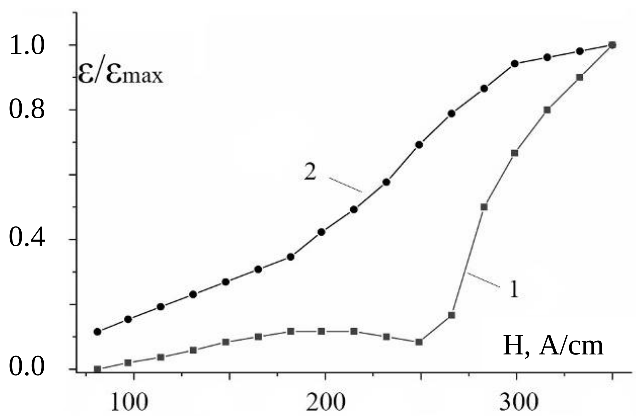

Figure 7. Dependence of the amplitude of the received Lamb ultrasonic waves on the intensity of the remagnetising field: 1 - at double frequency (without polarizing field); 2 - basic frequency (using polarizing field).

The material of a ferromagnet oscillates twice during one period of sinusoidal current in the exciting coil of a magnetostrictive transducer. In this case, the larger the field in the coil is, the greater the oscillations in a ferromagnet occur.

Under cyclical magnetization reversal, the amplitude of acoustic oscillations *P* will depend on the magnetostriction coefficient *M*, the external field strength *H* and the depth of the skin layer δ, since the larger the skin layer is, the greater the volume of the ferromagnet oscillates:

$$P \sim M(H_m) \cdot \delta(H_m) \tag{3}$$

The depth of the skin layer can be determined by the above equation (2) for determining the depth of the skin layer for a nonlinear case when calculating the parameters of a pulsed U-shaped electromagnet.

So, with large field strength there is no need for an additional displacement field, and at sufficiently large amplitudes of the exciting field, as it is shown in [7], the excitation efficiency without the displacement field will be the same to the excitation efficiency when using the bias field (figure 7).

3. Conclusion

Therefore, the highly effective emitter-receiver system may include:

- unidirectional primary EMATs;
- receiving EMAT with a normal magnetizing field (electrodynamic mechanism of EMA conversion), which is created by a magnetizing system of permanent magnets;
- radiating EMAT with a pulsed displacement field created by U-shaped electromagnet (magnetostrictive mechanism of EMA conversion);
- radiating magnetostrictive transducer that excites ultrasonic waves without a displacement field.

The proposed emitter-receiver system makes it possible to excite Lamb waves with great efficiency. It has minimal mass and dimensional characteristics, minimal attraction to a ferromagnet and opens up broad perspectives for the development of new devices for waveguide testing of ferromagnets. Further increasing of the sensitivity and removal of the dead zone near the EMATs can be achieved by using the technology of phased arrays [8].

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